



Feasibility Analysis and Uncertainty Quantification for a "Fast-Running" Chain of Codes for the NPP Accident Management

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Il presente documento descrive le attività di ricerca svolte all'interno dell'Accordo di collaborazione "Sviluppo competenze scientifiche nel campo della sicurezza nucleare e collaborazione ai programmi internazionali per il nucleare di IV generazione"

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Feasibility Analysis and Uncertainty Quantification for a "Fast-Running" Chain of Codes for the NPP Accident Management

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Sommario




This work briefly describes the computer codes RAVEN and DAKOTA, illustrating how to use them in the ambit of uncertainty quantification during PRA thermal hydraulic analyses. The second part shows instead two simple applications of RAVEN code to study SBO transient. In the first one, it has been coupled to RELAP-7 to analyze a PWR, in simplified manner (due to the current limitations of the RELAP-7 code, that is under development). In the second one, it was coupled to RELAP-5 3D code in order to analyze a BWR MARK-1. These two applications demonstrate the potential of the RAVEN code as an optimal tool for the coupling with codes for TH analyses.


Note

Questo documento è stato preparato col contributo congiunto del seguente personale di ricerca ENEA e CIRTEC:

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Acronyms

AC	Alternating Current
ADS	Automatic Depressurization System
BE	Best Estimate
BEPU	Best Estimate Plus Uncertainty
BDBA	Beyond Design Basis Accident
BWR	Boiling Water Reactor
DAKOTA	Design Analysis Kit for Optimization and Terascale Applications
DBA	Design Basis Accident
DC	Direct Current
ECCS	Emergency Core Cooling System
EDG	Emergency Diesel Generators
INL	Idaho National Laboratory (USA)
LOCA	Loss Of Coolant Accident
NPP	Nuclear Power Plant
NRC	US Nuclear Regulatory Commission
PWR	Pressurized Water Reactor
RAVEN	Reactor Analysis and Virtual control ENvironment
RELAP	Reactor Excursion and Leak Analysis Program
SBO	Station Black Out
SRV	Safety and Relief Valve
TH	Thermal-hydraulics

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1. Introduction


The nuclear reactor safety approach over the years has developed by following the three steps in the order listed below:

1. 1970 - 1990: Conservative evaluation model (EM)
2. •1990 – 2005: Best estimate code calculations, in particular for LOCA accident analysis
3. •2005 – present: best estimate code calculations plus uncertainty analysis (BEPU) for LOCA and non-LOCA accident analysis.

The evolution of the evaluation methods is mainly due to the continuous reduction of the computational time, which led first to be able to analyze with an increasing number of control volumes, introducing parallel models increasingly close to reality and subsequently led to estimate the uncertainties related to the variability of the input variables (initial and boundary conditions).

This study is aimed to analyze two of the computer programs used for the uncertainty analysis in the field of safety for nuclear reactors, DAKOTA and RAVEN.

Even knowing a priori that the two computer programs are both able to analyze the uncertainties, the work will only describe the actual use of DAKOTA in this field and to verify the main characteristics of the new computer programs RAVEN (which are described in a couple of case studies).

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2. Uncertainty quantification in TH analyses

To carry out deterministic safety analysis a best estimate (BE) thermal-hydraulic (TH) system computer programs are typically used. The two ways, requested for to guarantee safety demonstration with an adequate margin, are:

1. by use of the BE TH computer programs in combination with very conservative input data parameters;
2. by use of the same computer programs but with realistic (best estimate) input data parameters, added by a calculated uncertainty value.

The evaluation of uncertainty of the generated results ensures that they do not exceed a set of acceptance criteria.

The USA Code of Federal Regulation 10 CFR 50.46 [9], for example, allows either to use a best estimate code plus quantification of uncertainties, or the conservative option using conservative computer code models listed in Appendix K of the CFR, Title 10, Part 50.

Additionally, both methods require sensitivity analyses which aim to identify all potentially important parameters and to verify that there is no unexpected and consistent change in the calculated results.


The results of a computer program run are affected by uncertainties derived from different sources (program models, plant and fuel parameters error, approximations of modelling, variation of initial and boundary conditions. All of these potential error sources should be taken into account.

The analysis where performed with the use of the uncertainty quantification tool as, for example, DAKOTA or RAVEN.


In the TH application, the uncertainty tool calculates the input parameters for a TH computer program drawn from different probability density functions (usually normal and uniform ones determined in the engineering assessment process).

The program copies an existing input to a new input file, modifying the lines as instructed by well-placed comment cards and the parameters selected by the script. The new input deck is written to a file that has the indices of the selected input parameters attached to it to create a unique file name. This program is called prior to TH execution.

After this, the TH program is started with the created input file and these operations are repeated in loop. In conclusion, the output file are analyzed for the evaluation of the uncertainty.

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An advantage that is obtained by the use of these computer programs is the possibility to launch many cases in parallel on different cores, given that the TH computer programs are generally performed on single core.

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3. DAKOTA

DAKOTA (Design Analysis Kit for Optimization and Terascale Applications), developed by Sandia National Laboratory, is a reference tool for sensitivity/uncertainty analyses, selected by NRC and is open source. DAKOTA can handle an extended set of iterative methods, including optimization, sensitivity analysis, and uncertainty [11].

Dakota computer program provides a flexible and extensible interface between simulation codes and iterative analysis methods and contains algorithms for optimization, uncertainty quantification with sampling, reliability, and stochastic expansion methods, developed in particular for military nuclear applications.

The main capability, useful for S&U analysis and in Dynamic Probabilistic Risk Assessment, is the presence of a big set of sampling methods for the selection of perturbation values for each case.

3.1. *Coupling with TH computer programs*

In particular TH system computer program (e.g. RELAP5-3D, TRACE, etc.) could be externally coupled with DAKOTA to perform a sensitivity and uncertainty studies.

The coupling is realized by the means of a keywords inserted into a TH input file.


These keywords are the variables which are calculated by DAKOTA through a sampling.

In the DAKOTA input is possible to start the TH analysis and (after the end of the calculation) to evaluate the same (or other) variables in the TH output file.

This procedure must be iterative and the results will be a set of TH analyses which represents a source of information for the sensitivity and uncertainty studies.

Recently DAKOTA is integrated in Symbolic Nuclear Analysis Package (SNAP) as uncertainty tool.

INL is developing a specific tool (described in the Chapter 4) thought as an aid for the analyst for carrying out the Probabilistic Risk Assessment (PRA), fully integrated in RELAP5-3D and in future in RELAP-7.

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4. RAVEN


RAVEN (Reactor Analysis and Virtual control ENvironment) is a software framework (developed by INL) that acts as the control logic driver for the Thermal-Hydraulic code RELAP-7. RAVEN is PRA computer program that executes different functionalities. It is designed to derive and actuate the control logic required to simulate both plant control system and operator actions, and to perform both Monte-Carlo sampling of random distributed events and dynamic event tree based analysis. In order to facilitate the user in the writing and understanding of both the Input and the Output, a Graphical User Interface (GUI) and a post-processing data mining module, based on dimensionality and cardinality reduction, are available.

4.1. *Capabilities for a Probabilistic Risk Assessment*

RAVEN [6] has also been delegated the task of being an information manager: a differentiator of what is relevant or not to properly judge the risk. The Graphical User Interface (GUI) has been created to allow the generation of RELAP-7 input and analyzing the simulation results. The inspection of results visually is a fundamental aspect of engineering analysis. On top on what was just said there is also the fact that the RAVEN team is currently developing an environment where modern data mining techniques will be also available to the users. Those techniques will be used to separate the information and carefully detect the sources of risk in terms of key components, leading physical phenomena, or uncertainty sources. This information can be used in multiple ways: mitigation strategies can in fact be found through the identification of risk sources.

The capability to check over the plant evolution during the simulation is a must for uncertainty propagation, and it has to be a must for all PRA software. For these reasons, a strict interaction is needed between RELAP-7 and RAVEN. In many system safety analysis codes, the need to check over any facilities is expressed by the implementation of the control logic of such facilities. As a consequence, with the target in mind of optimizing the resources, there is the need to impose the integration of this task under a common project that is RAVEN. Consequently, the facility control logic is simulated by RAVEN. In such way, the code offers the flexibility to implement proprietary control logic without having to change RELAP-7 source code. This feature is also a factor for the quick dispatchment of RELAP-7 to the industry. In order to summarize, from a user prospective, RAVEN is a provider that:

- Easily generates complex plant layout including modeling information and control logic implementation (RELAP-7 GUI, and Control Logic)
- Allows following the simulation via visual interaction with the code while running

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- Determines the calculation flow to achieve the most accurate evaluation of risk accounting for probabilistic behavior and uncertainty propagation
- Visualizes simulations results (thousands and more) and provides the data mining capability to deeply understand the plant behavior
- Provides the capability to investigate risk mitigation strategies by suggesting directions and quickly assessing impacts

4.2. Dynamic Event Tree approach

In order to perform reliability and safety assessment of complex and critical engineering systems, the conventional Event Tree (ET) based methodologies are extensively used by the provider. These methods though have the disadvantages of not explicitly account for that timing/sequencing of events and system dynamics in the analysis, while it could be very important.

Another kind of approach is needed in order to overcome these limitations, what it is called a “dynamic” approach. In order to simulate system evolution in a way that is consistent with the progression of the accident scenario The Dynamic Event Tree (DET) technique is then needed. In the DET, event sequences are run simultaneously starting from a single initiating event. When the user provides the times and the physical conditions for it, the simulation will branch in the requested pathways. To clarify the methodology here are a couple of examples:

Branching at a certain point in time:

- A valve is set to start a new branch every n minutes where it moves its status from available to failed
- Valve starts the simulation being available
- After the first n minutes of simulation a parallel branch is started where the valve is failed (branch 2), while in the root simulation (branch 1) the valve is still available
- For the next n minutes the valve will be available in the branch 1 while failed in branch 2. This might lead to a different evolution of branch 1 with respect branch 2
- After an additional n minutes the branch 1 will create another branch (3) and so on

Branching at a given physical conditions:

- A valve has a certain probability to fail every time it gets used (failure on demand) by the control system
- Every time the control system demands the usage of the valve a new branch is generated where the valve is failed while the root branch move forward with the valve available

All kind of complex situations can be handled, like, for example, multiple outcomes (several branches started at the same time). The user has to set a time limit at which the branches will stop or an event which occurrence will also stop the simulation. The probability of each branch is associated to it. Each one represents the cumulative likelihood of the specific set of events leading the system to that branch. This is done in order to associate to a specific outcome its own probability. The figure below provides a visual representation of a DET evolution. The DET methodology has been developed in RAVEN and has been included in the RAVEN external Python manager (Artificial Intelligence Aided Discovery Framework).

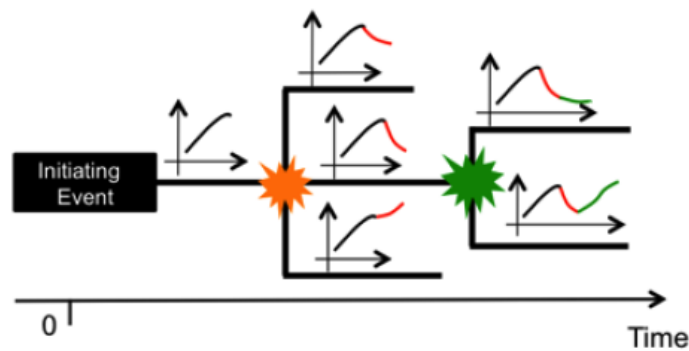


Figure 4.1 - Dynamic Event Tree Conceptual Scheme [4]

4.2.1. Description of the graphical input process

Input file creation begins by running the GUI from the directory containing the RELAP-7 code. An already existing input file with may also be specified, the software will read the already existing structure and therefore plot the results.

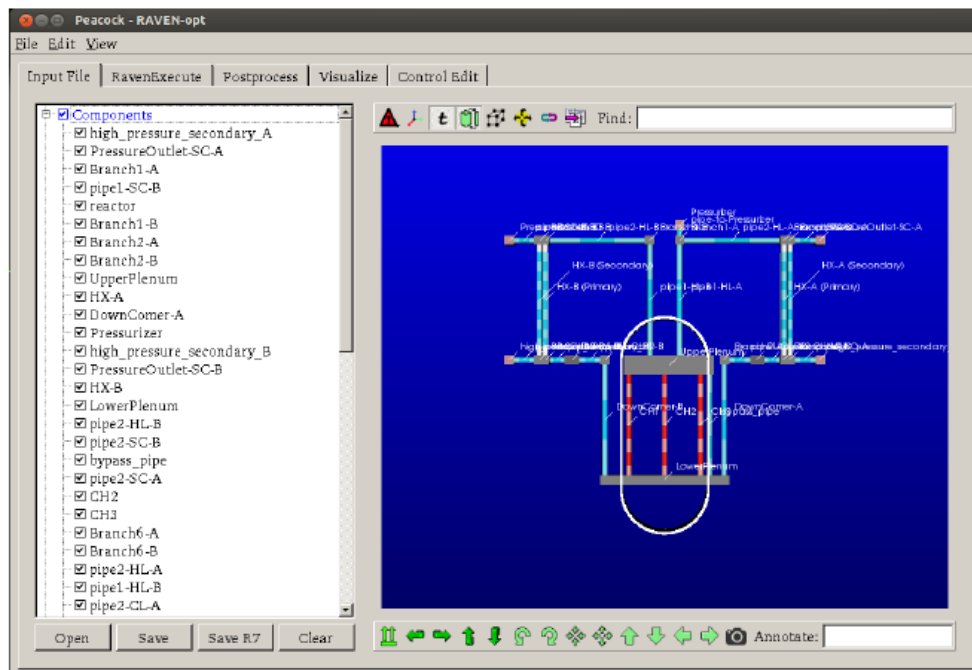


Figure 4.2 –simple PWR nodalization viewed in RAVEN GUI

The figure above shows the GUI specific to RAVEN. It includes the visual representation of the facility as well as many other control tabs. These tabs, after going to be filled out, and therefore saved, they will be automatically be safe inside the input file. The list of individual components is shown inside the section containing the structure of the facility. The checkboxes are used to quickly activate or deactivate particular parts of the input file. On the right side, the facility layout is shown. The user may navigate (pan, rotate, zoom) using either the mouse, or alternatively using buttons below the model display. The figure below shows a zoomed in view of the same model shown in the figure above with the navigation buttons highlighted. There can be shown all of the single components just by activating the relative check marks. In the figure below, this is being shown for “Down Comer-B” which is a pipe.

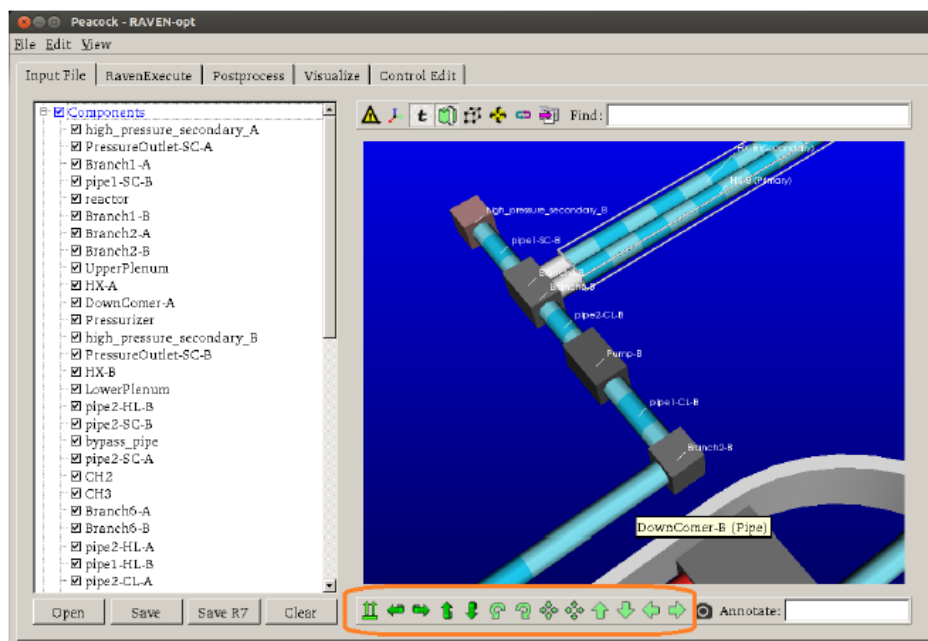



Figure 4.3 –detail of a PWR nodalization in RAVEN GUI

4.3. Software infrastructure

RAVEN has been developed in pluggable way, and also highly modular. in order to enable easy integration of different programming languages (i.e., C++, Python) and, coupling with any system code. Of course each system codes requires a specific set of files to allow the coupling. These files are pretty standard and can be achieved with a basic knowledge of the said programming languages.

Three main software systems compose RAVEN. All of these systems can operate either in coupled or stand-alone mode:


- Control Logic System
- Graphical User Interface
- Probabilistic and Parametric framework

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The control logic system and the Graphical User Interface are currently available for RELAP-7 only [5]. So far the attention has been focused on the probabilistic and parametric framework alone, exactly for this reason.

The core of the RAVEN analysis capabilities is represented by the probabilistic and parametric framework. A multi-purpose framework was needed. Such framework had to be characterized by high flexibility (with respect to the possible performable analysis). Such described framework is the main idea behind the design of the system as it is. The framework must be capable of constructing the analysis/calculation flow at run-time, interpreting the user-defined instructions and assembling the different analysis tasks following a user specified scheme. The language chosen to achieve such described flexibility was *python*, given its highly modular characteristics.

RAVEN is therefore characterized by an object-oriented design (typical of the python environment). The core of the analysis performable through RAVEN is represented by a set of basic components (objects) that the user can combine. All of this was set up in order to create a custom analysis flow. RAVEN employs a framework component called *Distribution*. In order to explore the input/output space, RAVEN requires the capability to perturb the input space (initial conditions of a system code). The initial conditions, that represent the uncertain space, are generally characterized by probability distribution functions (PDFs), which need to be considered when a perturbation is applied. In this respect, a large library of PDFs is available to choose from. It also employs a framework component called *Sampler*: Each variable inside the input space needs to be perturbed. RAVEN employs different kinds of these perturbations methods, each with a much different computational time requirement and therefore resolution. Different kinds of samplers can be adapted to different situations/plant requirements. Also, inside each sampler there are many options available (chosen from the distribution framework component) in order to best adapt the user requirements. It also employs a framework component called *Model*: A model is the representation of any system the user needs to meet its requirements, in can be set up to represent any kind of evolution inside a determinate facility; it is therefore capable of predicting the evolution of such specified system given a description set in the input space. It also employs a framework component called *Reduced Order Model (ROM)*: They can be considered as an artificial representation of the link between the input and output space for a particular system. Many times the computational effort needed to run a code (such as thermohydraulic code) might be too heavy to achieve, especially when brute-force approaches (e.g. Monte Carlo methods) are chosen as the sampling strategy. Reduced Order Models are used to lower the computational effort, reducing the number of needed points through the use of "fitting" strategies that adapt the algorithm used in a determinate input space. Also included are modules related to visualization and storage infrastructure. RAVEN uses fast accessible database files, called HDF5, with an .h5 extension.

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4.4. Raven Approaching Dynamic Methodologies: ANDREA Module

The newly developed module "ANalysis of Dynamic REactor Accident evolution" RAVEN is now able to perform DET analysis. Following the philosophy of the DET approach, this module lets RELAP-7 find the path of an accident sequence, in a probabilistic point of view. When the system achieves certain conditions that would lead to alternative accident ways (i.e. an event occurs), a sampler generates a new set of branches (new possible scenarios), associating for each a conditional probability.

For the analysis of complex systems, the number of branches may become extremely big. In order to avoid unacceptable growth of problem due by an excessive number of branches, the user needs to specify an exit logic (termination laws), for example maximum mission time, rules based on the simulator physic model (i.e. Maximum temperature of the fuel cladding, etc.), and/or probabilistic thresholds. In other similar codes, one of the most common termination law is a probability cut-off: a branch execution is stopped when its probability falls below a given limit.


This approach may introduce a big impact on the probability of key events, if the user defined limit is not small enough that the influence on the final branch probability is not negligible. In order to avoid these issues and preserve the probability conservation, the user can not directly input, in RAVEN, a branching probability cut-off [1].

As can be inferred from above, RAVEN provides capabilities to:

- explore possible pathways through which the system can evolve
- quantify the probability of these scenarios

These main tasks are accomplished based on user specified branching and termination laws, model of the system in RELAP-7, probability assignment rules to accident sequences (either by inputted values or/and by distribution functions). The synergy among the different RAVEN modules gives to the package the flexibility to summarize all the state of art DET capabilities. Indeed, as in similar tools, the RAVEN/ANDREA allows the user to use different approaches for defying the branching logic:

- branching/failures on demand (i.e. time and field triggers)
- branching based on failure probability distributions
- multi-branching scenarios

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The list above, gives an indication on how RAVEN (and the DET module) combines the capabilities present in other similar codes.

In RAVEN there is no distinction between active (e.g. circulation pumps, valves, controlled systems, etc.) and passive (e.g. steam generators, condensers, pipes, etc.) component behaviors; all are treated as a aleatory uncertainties, since the physical conditions under which a branching would occur for the them are determined by the thermal-hydraulic code RELAP-7 without user “control”. The user can model also the epistemic uncertainties, uncertainties due by lack of knowledge on the phenomena analyzed (e.g. Heat capacity coefficient, etc.).

In RAVEN, from an user point of view, either the aleatory and epistemic uncertainties are undifferentiated, since the branching laws are inputted in the same way. All triggers are identified by their own PDFs and activated when an user defined probability threshold, on the associated Cumulative Distribution Function (CDF), is overpassed. The probability thresholds on the CDFs are automatically handled by the DET module; the user only needs to specify them in the input.

4.4.1. Demo For a PWR PRA Analysis

In order to show the capabilities of RAVEN coupled with RELAP-7, a simplified PWR PRA analysis has been employed [4]. The Figure 4.4 shows the scheme of the PWR model. The reactor vessel model consists of the Down-comers, the Lower Plenum, the Reactor Core Model and the Upper Plenum. Core channels (flow channels with heat structure attached to each of them) were used to describe the reactor core. The core model consists of three parallel core channels and one bypass flow channel. There are two primary loops, i.e., loop A and loop B. Each loop consists of the Hot Leg, a Heat Exchanger and its secondary side pipes, the Cold Leg and a primary Pump. A pressurizer is attached to the Loop A piping system to control the system pressure. A Time Dependent Volume (pressure boundary conditions) component is used to represent the Pressurizer. Since the RELAP-7 code does not have the two-phase flow capability yet, single-phase counter-current heat exchanger models are implemented to mimic the function of steam generators in order to transfer heat from the primary to the secondary. In order to perform a PRA analysis on this simplified model, it has been necessary to control unconventional parameters (i.e. inlet/outlet friction factors), since RELAP-7 still has limitations for the component controllable parameters and models. In the following paragraph, the PRA station black out sequence of events is reported.

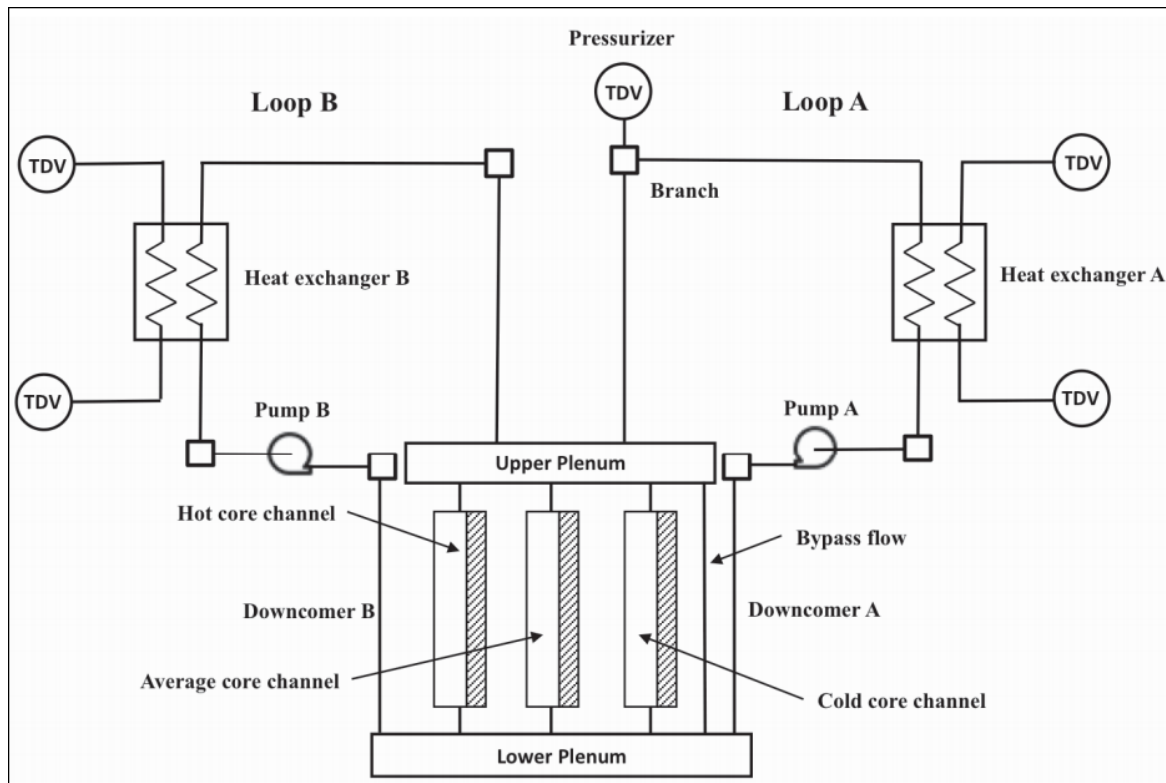


Figure 4.4 - PWR model scheme [4]

The Probabilistic Risk Assessment analysis has been performed simulating a Station Black Out accident, making Monte-Carlo samplings on the recovery time of the diesel generators t_1 (delta time from reactor scram signal) and the clad failure temperature T_{cf} . Two sets of Monte-Carlo calculations have been run:

- 400 runs, randomizing t_1 (Normal distribution, $\mu = 120$ s, $\sigma = 20$ s) and T_{cf} (Triangular distribution, $x_{Peak} = 1477.59$ K, $x_{Min} = 1255.37$ K, $x_{Max} = 1699.82$ K)
- 400 runs, randomizing only t_1

The SBO transient is based on the following sequence of events (starting from a steady-state operational condition of the Nuclear Power Plant):

- 60.0 seconds, transient begins
- 61.0 seconds, loss of power grid and immediate shutdown of the reactor(scram):
 - Pump coast-down;
 - Decay heat power;
 - Diesel Generators and residual heat removal system (RHRS) not available.
- t_1 , recovery of the diesel generators
- t_2 , end of transient either for clad failure or 300 seconds of simulation (PRA success)

Since the scope of this demo is to show the capabilities contained in RAVEN and RELAP-7 capabilities are not optimized for long simulation times, the transient has been accelerated in order to simulate a maximum of 300 seconds. In the following paragraph, the simulations results are shown and explained.

The next figure shows the distribution of the maximum temperature reached by the clad in the core channels (blue histogram) and compares it with the distribution of clad failure temperature (red histogram). The distribution of the clad temperature already accounts for the simulations that have been stopped for having reached the corresponding failure temperature. Therefore, the overlapping of the two distributions is not representative of the total failure rate. Instead, the total failure rate could be inferred from the steep decrease on the higher temperature side of the number of counts with respect the lower temperature one. The probability of failure is artificially elevated with respect a real case in order to keep the effort bounded while illustrating the full RAVEN capabilities.

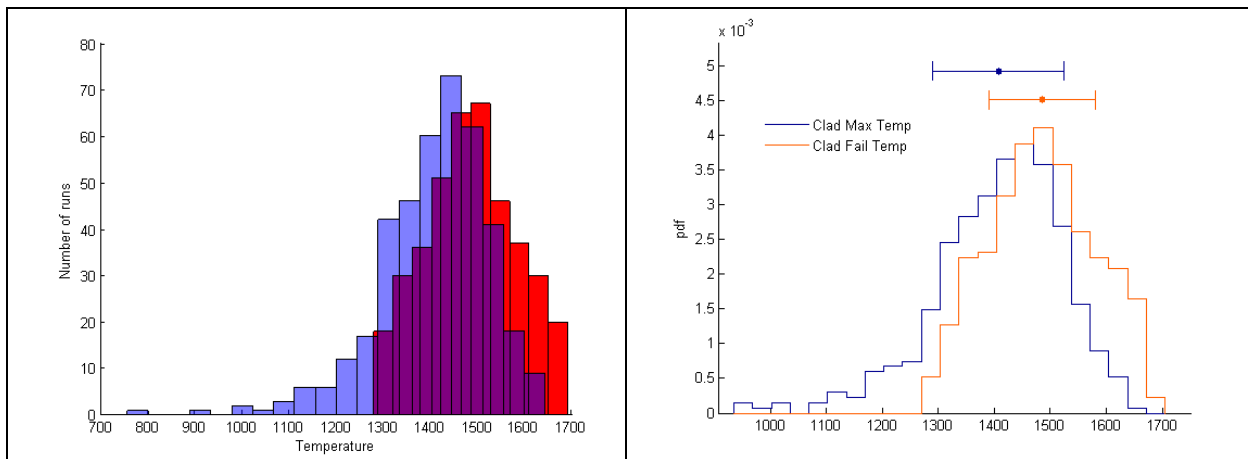


Figure 4.5 - Comparison between max reached clad temperature and clad failure temperature distributions [4]

In addition, the next figure shows the limit surface, i.e. the boundaries between system failure (red points) and system success (green points), obtained by the 400 Monte-Carlo simulations. Since only two uncertain parameters have been considered (i.e., DG recovery time and clad fail temperature), this boundary lies in a 2-dimensional space. The slope of the limit surface pictured in the next figure also shows, in this particular demo, how the DG recovery time has a greater impact on the system dynamics than the clad failure temperature (this is confirmed also when rescaling the graph in term of relative deviation from the average values).

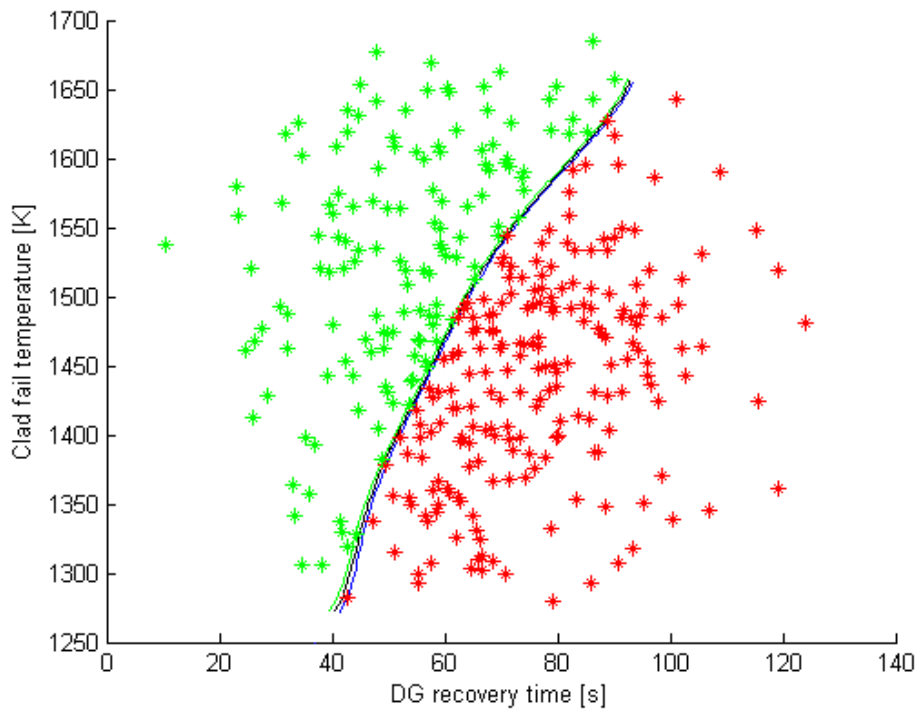


Figure 4.6 - Limit Surface for the SBO analysis of a simplified PWR model [4]

It has also been performed a new set of 400 Monte-Carlo simulations in which, now, the clad failure temperature is fixed at a predefined value $T_{Fail} = 1477.59$ (i.e., there is no triangular distribution associated to it). As expected, the number of simulations that let to system failure was slightly different among these two sets of simulations: 203 for the first case and 224 for this last one. This fact shows how modeling of uncertainties can impact risk evaluation.

4.4.2. Demo For a BWR PRA Analysis

It is now presented a BWR Mark I. In such power plant there are going to be sampled three variables: Diesel Failure Time, Diesel Recovery Time and the Power Level. For the diesel failure time the distribution followed is a normal with a mean of 26460 seconds and a sigma of 5400 seconds. The recovery time is exponential, with a lambda of $2.5 \cdot 10^{-6}$ and an upper bound of 28800 seconds. The power distribution is uniform, ranging from 100% up to 120%. With the MonteCarlo sampling of these variables, in a 4d image there are the following results:

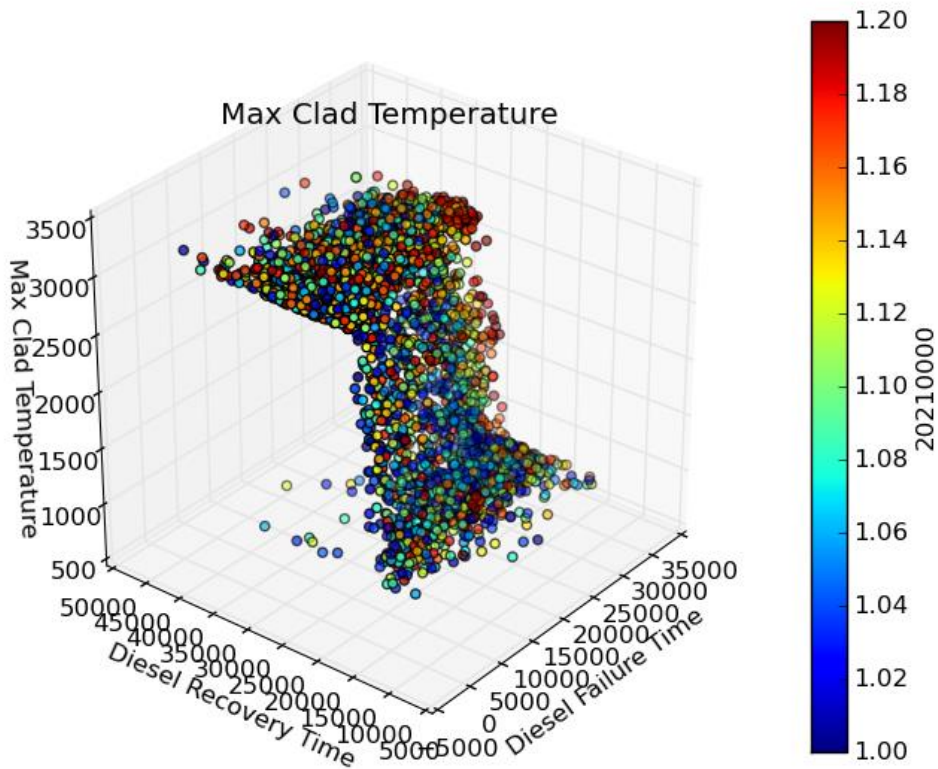


Figure 4.7 - BWR Probabilistic Risk Analysis using RELAP5-3D and RAVEN

The variable in output is the temperature at which the clad is situated. A upper limit on the temperature was set, which was the cladding failure temperature. If the point is to be found inside the upper part of the graph then there is going to be cladding failure. This shows how it is possible to determine on which "surfaces" the plant can be situated in safe conditions even with ongoing accidents.

The MonteCarlo sampling is not the only one available in RAVEN. The MonteCarlo requests a high computational power, not always available. So different kinds of sampling methods are used. In the following images there can be seen a Grid Sampling. Instead of the randomness of a MonteCarlo the Grid sampling follows a precise grid pattern, thus reducing the computational power needed.

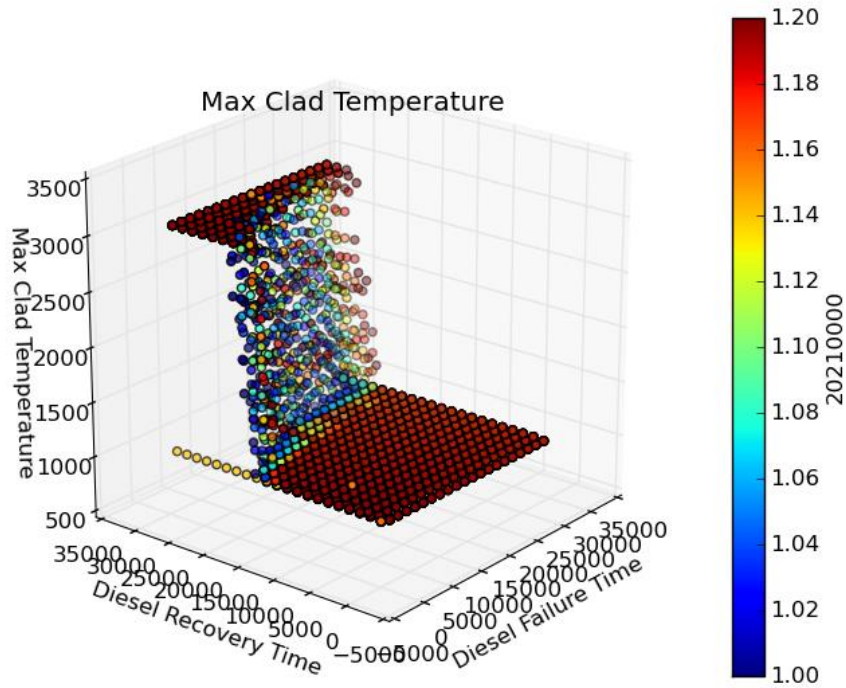


Figure 4.8 - BWR Probabilistic Risk Analysis using RELAP5-3D and RAVEN [12]

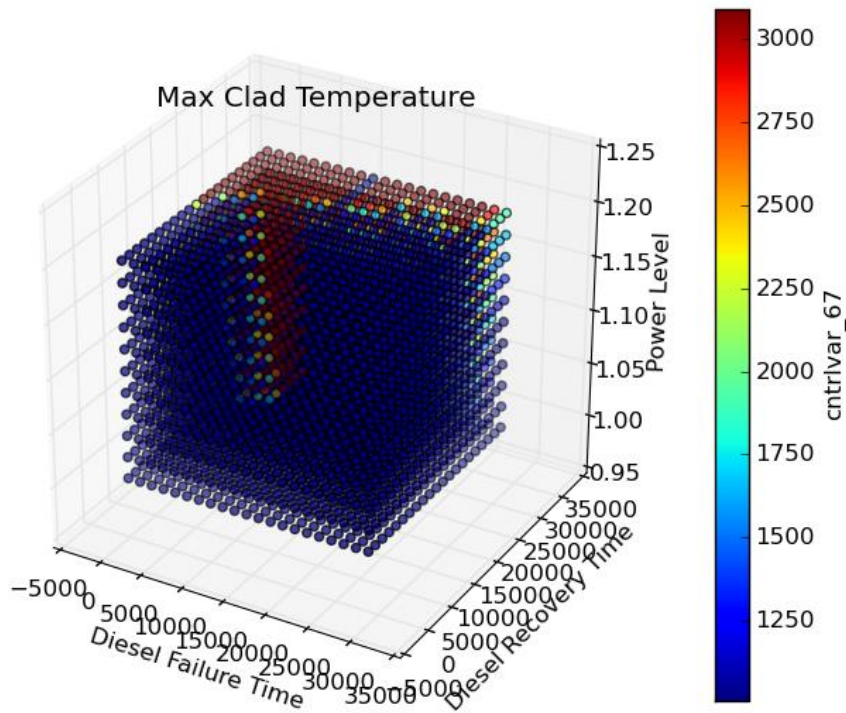


Figure 4.9 - BWR Probabilistic Risk Analysis using RELAP5-3D and RAVEN [12]

These sampling methods allow RAVEN to determine the "limit surface". Such surface is the boundary between the safe region and the failure region. Limit surfaces are mathematical constructs that separate the input space between regions leading to success or failure.

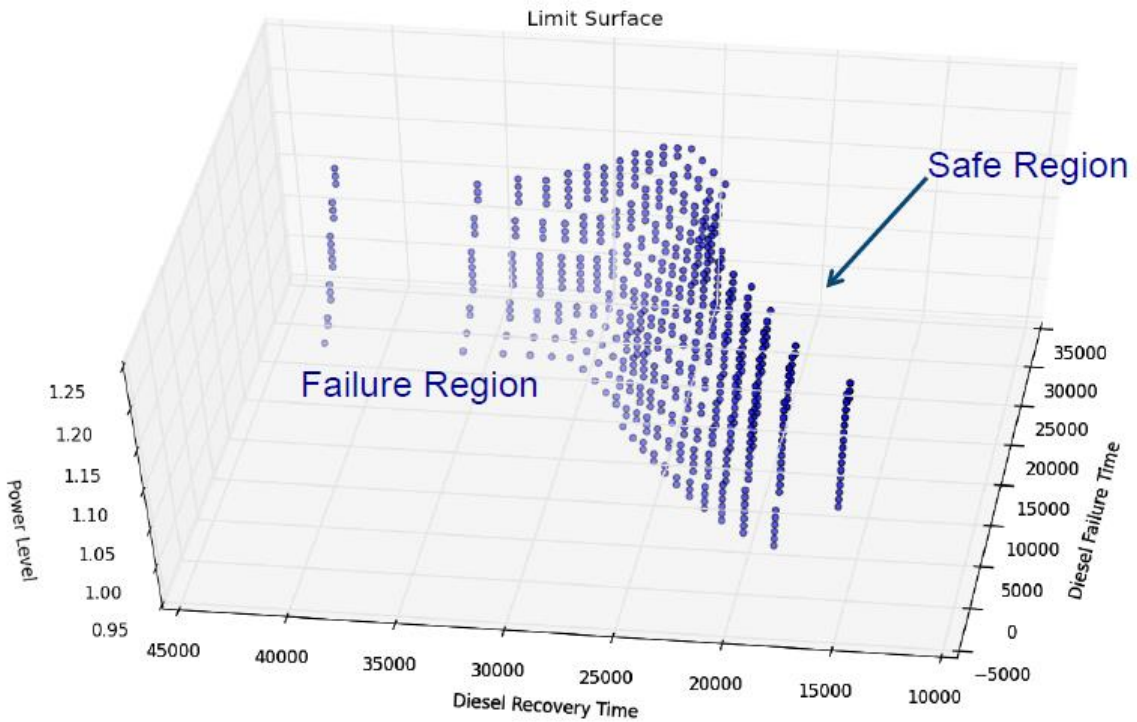




Figure 4.10 - BWR Probabilistic Risk Analysis using RELAP5-3D and RAVEN [12]

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5. Conclusions

RAVEN is distributed to many universities around the world and it is continuously updated and upgraded to fit any user who has requirements of sampling/probabilistic prediction. It has been successfully coupled with many thermo-hydraulic codes, it is being developed to be coupled with weather-prediction software, and given its modular form can be coupled, in unbeatable time, to almost any code the user is fit to suffice. Its extremely powerful accelerating mechanisms allow for fast checking of any initial model before it can be run on a super computer. Having the capability of running on parallel on many processors gives the code high adaptability to any kind of calculation/complexity the user has desire of.

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